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CARRIER-INDUCED FERROMAGNETISM IN Ga1-xMnxAs
SUBMICRON MAGNETOMETRY WITH MICROMECHANICAL CANTILEVERS: SINGLE SPIN SENSITIVITY
DEMONSTRATION OF AN ALL-SEMICONDUCTOR SPIN-INJECTION DEVICE
OBSERVATION OF ELECTRON SPIN COHERENCE IN GaN

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- ***Carrier-induced ferromagnetism in $Ga_{1-x}Mn_xAs$***

A distinguishing feature of diluted magnetic semiconductors (DMSs) is the coupling of electrons and holes to a population of local magnetic moments. This leads to a number of interesting properties, including an enhanced g-factor for carriers as well as novel excitations such as magnetic polarons. Ferromagnetism, however, is rarely observed in semiconductors, which is a consequence of both the low density of carriers and the prevalence of antiferromagnetic superexchange among local moments. As a result, most ferromagnetic semiconductors are relatively exotic systems with low Curie temperatures. The recent achievement of Curie temperatures over 100 K in the III-V DMS $(Ga_{1-x}Mn_x)As$ at moderate Mn concentrations ($x \sim 0.05$) is therefore particularly significant. This material offers the possibility of exploiting traditional techniques for controlling the carrier population in a semiconductor in order to realize a new class of tunable ferromagnetic devices. Identifying the role of charge carriers in the ferromagnetic exchange mechanism in $(Ga_{1-x}Mn_x)As$ is therefore a high priority, and is the basis for creating ferromagnetism in this new family of semiconductors. Here we have performed a systematic study of the magnetic circular dichroism (MCD) in $(Ga_{1-x}Mn_x)As$ which identifies the critical role played by holes in the ferromagnetic exchange mechanism. We observe an unusual MCD signal comprising two contributions: a broad spectrum that scales with the thermodynamic magnetization of the sample and a narrower peak (~150 meV FWHM) which appears only in the ferromagnetic phase. This peak is attributed to the spontaneous spin splitting of the hole density of states. The sign of the peak indicates that the exchange between the holes and the local Mn moments is antiferromagnetic. We find ferromagnetism and the unusual MCD behavior in both metallic and insulating samples. This observation, along with the large spin polarization that can be inferred from transport measurements, suggests that the holes in $(Ga_{1-x}Mn_x)As$ do not simply play the role of a Fermi sea mediating a Ruderman-Kittel-Kasuya-Yosida (RKKY)-like exchange interaction. This work appeared as, "Magnetic Circular Dichroism Studies of Carrier-induced Ferromagnetism in $(Ga_{1-x}Mn_x)As$," *Phys. Rev. Lett.* **83**, 3073 (1999).

- ***Submicron magnetometry with micromechanical cantilevers: single spin sensitivity***

We directly measure the magnetization of conduction electrons and Mn^{2+} ions in (Zn,Cd,Mn)Se two dimensional electron gases (2DEGs) by integrating them into micromechanical magnetometers. The interplay between spin and orbital energy in these magnetic 2DEGs causes Landau level degeneracies at the Fermi energy, resulting in a number of unusual features in the deHaas-Van Alphen oscillations. These are reproduced by simple thermodynamic calculations that ignore Landau level mixing. We find that the magnetometers are potentially capable of detecting the spin-lattice relaxation of a single Mn^{2+} moment.

The quantum Hall effect in two dimensional electron gases (2DEGs) arises in large part from the interplay between delocalized, current-carrying states near the center of each Landau level and localized states which lie between the Landau levels. Transport measurements probe the delocalized states near the Fermi energy, but provide very little direct information about the total density of states (DOS) of a 2DEG. In contrast, measurements of magnetization (or any other thermodynamic quantity) are a powerful tool for exploring the total DOS of a degenerate

Fermi gas. Recent advances in high-sensitivity magnetometry have allowed magnetization studies of single 2DEGs in the quantum Hall regime, providing new insights into the DOS, such as the appearance of true cyclotron gaps only for high mobility (~ 10^6 cm^2/Vs) samples, wide sample-to-sample variations of the spin-resolved deHaas-vanAlphen (dHvA) oscillations, the absence of a simple Landau level (LL) line shape, and the appearance of gaps at fractional filling factors. Here, we employ newly-developed micromechanical cantilever magnetometers (with a moment sensitivity ~$3x10^5$ μ_B in a field of 4 T) to probe the magnetization of "magnetic" 2DEGs wherein the *s-d* exchange-coupling between two-dimensional conduction electrons and local magnetic moments (Mn^{2+} ions) creates a highly enhanced spin-splitting of the 2DEG. This splitting can be larger than the cyclotron energy, leading to accidental degeneracies (or "crossings") of LLs. As a result, we observe fully spin-resolved dHvA oscillations with unusual properties: the dHvA oscillations do not follow the standard "1/B" periodicity, and the positions of the dHvA extrema are strongly temperature-dependent. These unusual effects are reproduced in detail by thermodynamic calculations which include the re-ordering of the LLs due to the giant spin-splitting, but which do not include any effects of LL mixing. We note that the influence of LL mixing on both localized and delocalized states remains a fundamental (and largely unresolved) issue in the physics of the quantum Hall effect, both in the limit of zero magnetic field and at high fields in samples with more than one occupied subband. In addition, we measure a strongly temperature-dependent coupling of the paramagnetic Mn moments to the motion of the cantilever, demonstrating a dissipation sensitivity equivalent to the spin-lattice relaxation of a single Mn ion. This work appeared as, "Magnetization Measurements of Magnetic Two-dimensional Electron Gases," *Phys. Rev. Lett.*, **86**, 4644 (2001).

GaAs	100 Å
$Al_{0.3}Ga_{0.7}As$	700 Å
$Al_{0.3}Ga_{0.7}As$	400 Å
GaAs	6000 Å
$Al_{0.8}Ga_{0.2}As$	1000 Å
GaAs	1000 Å
$Al_{0.8}Ga_{0.2}As$	3000 Å
SI GaAs	Substrate

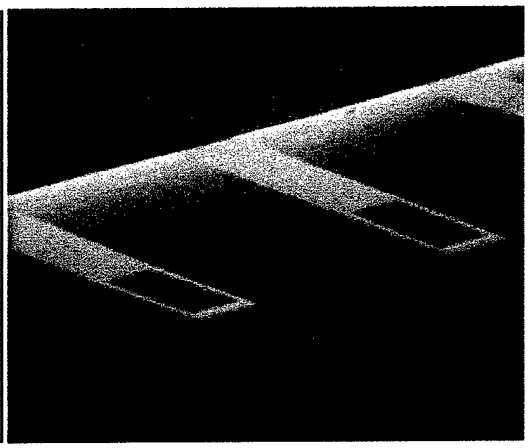

Figure 1. Details of MBE grown sample. The cantilever is fabricated from the 1000 A thick GaAs epilayer. Right: SEM photo of two finished cantilevers (320 μm long, 50 μm wide and 0.1 μm thick. The rectangular mesas containing the 2DEGs are 100 μm long and 40 μm wide.

- ***Demonstration of an all-semiconductor spin-injection device***

We reported the first fabrication and demonstration of all-semiconductor spintronic devices using III-V heterostructures based on GaAs, where electrical spin injection occurs in *zero* magnetic field from a ferromagnetic semiconductor into a non-magnetic semiconductor quantum well (QW). They employ *p-n* junctions into which polarized holes are introduced from a p-type

ferromagnetic semiconductor (Ga,Mn)As, and unpolarized electrons are injected from an n-type GaAs substrate. The hole spin polarization is directly measured by analyzing the polarization of the emitted electroluminescence (EL) from an embedded (In,Ga)As QW placed at discrete locations from the ferromagnetic region, revealing spin-polarized hole transport over surprisingly large distances in semiconductors. The magnetic field dependence of the EL polarization exhibits hysteresis below the ferromagnetic transition temperature of (Ga,Mn)As, with sharp switching fields of < 40 G. This represents new opportunities for fundamental science and technology in spin-based electronic transport within magnetic nanostructures, and is the first ferromagnetic semiconductor spintronic device. This work appeared as, "Electrical Spin Injection in a Ferromagnetic Semiconductor Heterostructure," *Nature* **402**, 790 (1999).

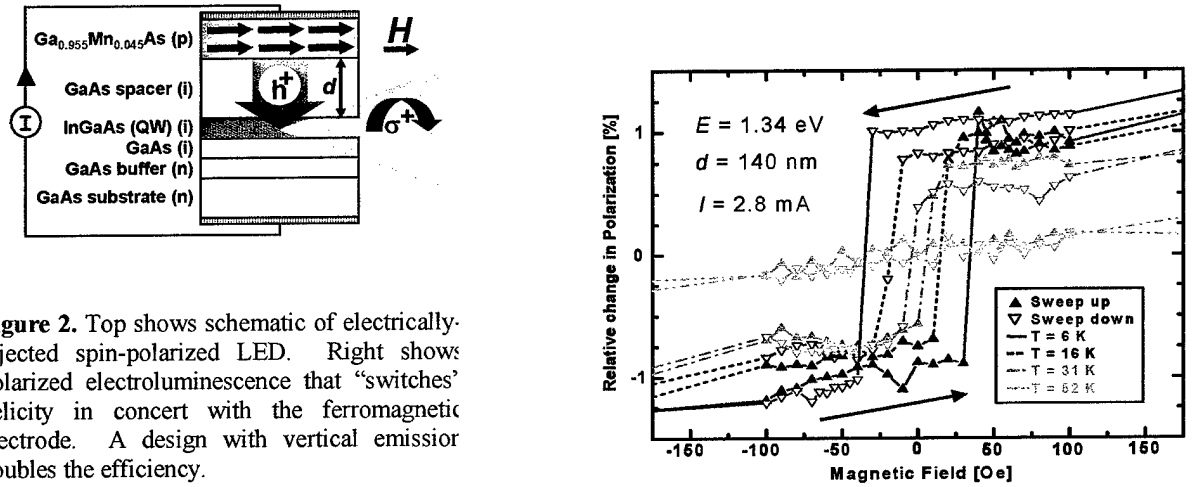

Figure 2. Top shows schematic of electrically-injected spin-polarized LED. Right shows polarized electroluminescence that "switches" helicity in concert with the ferromagnetic electrode. A design with vertical emission doubles the efficiency.

- ***Observation of electron spin coherence in GaN***

There is an emerging interest in the exploitation of electron spins in semiconductors to realize all-semiconductor electronic devices such as spin diodes or non-volatile spin memory. The successful realization of these devices necessitates the ability to inject and preserve spin information over practical device length and time scales. Recent observations revealing extremely long spin coherence times for optically injected spins in non-magnetic semiconductors, as well as spin transport over macroscopic distances and through semiconductor heterointerfaces, has additionally raised the possibility that these spin-coherent properties may eventually enable quantum computational operations in solid state systems. In this context, the III-V semiconductor GaN and its related ternary compounds are intriguing in that they combine a high density of charged threading dislocations (typically $10^8 - 10^{10}$ cm^{-2}) with high optical quality. As a result, it is possible to optically create and monitor coherent electronic spin states in a system where crystalline defects may play an important role in spin dephasing and decoherence mechanisms. Here, we use the optical pump/probe technique of time-resolved Faraday rotation (TRFR) to systematically investigate spin coherence in a series of n-type GaN epilayers grown by metal-organic chemical vapor deposition (MOCVD), with carrier concentrations ranging from the insulating to the metallic regime. Despite the dislocation density in these samples, the data reveal a tri-exponential decay with surprisingly long spin lifetimes of up to ~ 20 ns observed at

$T = 5$ K. The spin coherence persists to room temperature and exhibits similar behavior to other III-V and II-VI semiconductors grown by molecular beam epitaxy with many orders of magnitude fewer defects, suggesting that the spin degree of freedom is largely insensitive to momentum scattering from the charged threading dislocations. Similar spin coherence has also been observed in $In_xGa_{1-x}N$, suggesting that it is robust to high defect densities in a variety of materials. These findings are promising for the potential development of optoelectronic devices that rely on the coherent properties of the electron spin. This work appeared as, "Spin Coherence and Dephasing in GaN," *Phys. Rev. B* Rapid Communications **63**, R121202-1 (2001).

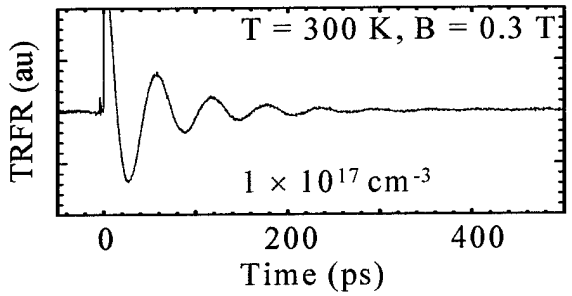

Figure 3. TRFR taken in a magnetic field of 0.3 Tesla and a temperature of 300K in a n-doped GaN epilayer with $n=1x10^{17}$ cm –3. This coherence time increase to over 20 nanoseconds at a temperature of 5K.

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2. B. Beschoten, P. A. Crowell, I. Malajovich, D. D. Awschalom, F. Matsukura, A. Shen, and H. Ohno, "Magnetic Circular Dichroism Studies of Carrier-induced Ferromagnetism in $(Ga_{1-x}Mn_x)As$," *Phys. Rev. Lett.* **83**, 3073 (1999).
3. J.A. Gupta, D. D. Awschalom, X. Peng, and P. Alivisatos, "Spin Coherence in Semiconductor Quantum Dots," *Phys. Rev. B (Rapid Communications)* **59**, R10421 (1999).
4. D. D. Awschalom and J. M. Kikkawa, "Electron Spin and Optical Coherence in Semiconductors," Invited Article, *Physics Today* **52**, 33 (June, 1999).
5. J. G. E. Harris and D. D. Awschalom, "Thin Films Squeeze Out Domains," Invited Article, *Physics World* **12**, 19 (1999).
6. J.B. Kortright, D. D. Awschalom, J. Stöhr, S. D. Bader, Y. U. Idzerda, I. K. Schuller, S. S. P. Parkin, and H.C. Siegmann, "Research Frontiers in Magnetic Materials at Soft X-Ray Synchrotron Facilities," Invited Article for the Special Volume 200 "Magnetism Beyond 2000," *J. Mag. Mag. Mat.*, in press (1999).
7. D. K. Young, M. O. Mack, A. C. Abare, M. Hansen, L. A. Coldren, S. P. Denbaars, E. L. Hu, and D. D. Awschalom, "Near-Field Scanning Optical Microscopy of Indium Gallium Nitride Multiple-Quantum-Well Laser Diodes," *Appl. Phys. Lett.* **74**, 2349 (1999).
8. J. G. E. Harris, J. E. Grimaldi, and D. D. Awschalom, "Excess Spin and the Dynamics of Antiferromagnetic Ferritin," *Phys. Rev. B* **60**, 3453 (1999).
9. D. D. Awschalom and N. Samarth, "Spin Dynamics and Quantum Transport in Magnetic Semiconductor Quantum Structures," Invited Article for the Special Volume 200 "Magnetism Beyond 2000," *J. Mag. Mag. Mat* **200**, 130 (1999).

10. D. D. Awschalom and N. Samarth, "Injection and Transport of Spin Coherence in Semiconductors," in *Physics and Chemistry of Nanostructured Materials* [Taylor and Francis, London, 1999].
11. J. G. E. Harris, D. D. Awschalom, F. Matsukura, H. Ohno, K. D. Maranowski, and A. C. Gossard, "Integrated Micromechanical Cantilever Magnetometry of $Ga_{1-x}Mn_xAs$," *Appl. Phys. Lett.* **75**, 1140 (1999).
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13. Y. Ohno, D. K. Young, B. Beschoten, F. Matsukura, H. Ohno, and D. D. Awschalom, "Electrical Spin Injection in a Ferromagnetic Semiconductor Heterostructure," *Nature* **402**, 790 (1999).
14. D. D. Awschalom and N. Samarth, "Coherent Spin Dynamics and Spin Polarized Transport in Doped Semiconductors," Invited Paper, *Journal of Superconductivity: Incorporating Novel Magnetism* **13**, 201 (2000).
15. S.A. Crooker, E. Johnston-Halperin, D. D. Awschalom, R. Knobel, and N. Samarth, "Stability of Trions in Strongly Spin Polarized Two-Dimensional Electron Gases," *Phys. Rev. B* Rapid Communications, **61**, R16307 (2000).
16. J. M. Kikkawa, J. A. Gupta, I. Malajovich, and D. D. Awschalom, "Spin Coherence in Semiconductors: Storage, Transport, and Reduced Dimensionality," Invited Paper for the Eleventh International Winterschool on New Developments in Solid State Physics, Mauterndorf, Austria, February 21-25, 2000, *Physica E* (2000).
17. J. G. E. Harris, R. Knobel, K. D. Maranowski, A. C. Gossard, N. Samarth, and D. D. Awschalom, "Magnetization Measurements of Magnetic Two-dimensional Electron Gases," *Phys. Rev. Lett.*, **86**, 4644 (2001).
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21. R. Knobel, N. Samarth, J. G. E Harris, and D. D. Awschalom, "Landau Level Crossings and Excited-state Mapping in Magnetic Two-dimensional Electron Gases," *Phys. Rev. B* Rapid Communications, submitted (2001).

Invited Presentations:

1. D. D. Awschalom, Workshop on Mesoscopic Superconductivity and Magnetism, Argonne National Laboratory, November 18, 2001.
2. D. D. Awschalom, XII International Conference on Ultrafast Processes in Spectroscopy (UPS-2001), Florence, Italy, October 28 – November 1, 2001.

3. D. D. Awschalom, Second European Workshop on Quantum Information Processing and Communication (QIPC), ISI Torino, Italy, October 28-31, 2001.
4. D. D. Awschalom (declined), Physical Phenomena in High Magnetic Fields-IV, Santa Fe, NM, October 19-25, 2001.
5. D. D. Awschalom, "Manipulation and Storage of Quantum Information with Semiconductor Spintronics," Center for Nanoscience Workshop on Physics at the Nanoscale, Venice International University, Venice, Italy, September 23-29, 2001.
6. D. D. Awschalom (declined), "Quantum Coherence and Computation in Semiconductor Nanostructures," Conference on Quantum Computing and Communication, University of Georgia, Athens, GA, September 21-23, 2001.
7. D. D. Awschalom, "Manipulation and Storage of Quantum Information with Semiconductor Spintronics," Tenth International II-VI Semiconductor Conference, Bremen, Germany, September 9-14, 2001.
8. D. D. Awschalom, "Semiconductor Spintronics and Coherence Spin Dynamics," 12th International Conference on Hot Carriers in Semiconductors, Santa Fe, NM, August 27-31, 2001.
9. I. Malajovich (and D. D. Awschalom), Spintronics 2001: Novel Aspects of Spin-Polarized Transport and Spin Dynamics, Georgetown University, Washington, DC, August 9-11, 2001.
10. D. D. Awschalom, Workshop on Spins in Nanostructures, Aspen School for Theoretical Physics, July 30 – August 17, 2001.
11. D. D. Awschalom, Symposium on the Future of Materials Physics, (Festschrift for Zachary Fisk), Los Alamos National Laboratory, Los Alamos, NM, August 13-15, 2001.
12. D. D. Awschalom, Fundamental Optical Properties in Semiconductors (AMFOPS), Anchorage, Alaska, August 5-10, 2001.
13. D. D. Awschalom, "Manipulation and Storage of Quantum Information with Semiconductor Spintronics," 10th International Conference on Modulated Semiconductor Structures (MSS-10), University of Linz, Austria, July 23-27, 2001.
14. D. D. Awschalom (declined), NSF Panamerican Advanced Study Institute on "Physics and Technology at the Nanometer Scale," San Jose, Costa Rica, June 25- July 3, 2001.
15. B. Beschoten (and D. D. Awschalom), "Spin Coherence and Dephasing in GaN," 4th International Symposium on Metallic Multilayers (MML'01), Aachen, Germany, June 24-29, 2001.
16. D. D. Awschalom, Symposium on Spin and Coherent Phenomena in Nanostructures, Meeting of the Italian National Institute of Condensed Matter Physics (INFM), Rome, Italy, June 18-22, 2001.
17. D. D. Awschalom, Gordon Research Conference on Magnetic Resonance, Bristol, RI, June 17-22, 2001.
18. D. D. Awschalom, Advanced Research Workshop on Quantum Transport in Semiconductors, Maratea, Italy, June 17-22, 2001.
19. D. D. Awschalom, 15th International Conference on Laser Spectroscopy, Snowbird, UT, June 10-16, 2001.

20. D. D. Awschalom (declined), Inauguration of the Institute of NanoScience and Technology (INST), Hong Kong University of Science and Technology, Hong Kong, China, May 15-16, 2001.
21. D. D. Awschalom (declined), Eleventh Conference on Computational Research on Materials, Lakeview Resort and Conference Center, Morgantown, WV, May 9-11, 2001.
22. D. D. Awschalom (declined), Physics Department Colloquium, California State University, Northridge, CA, May 9, 2001.
23. D. D. Awschalom, "Spintronics and Quantum Information Processing in Semiconductor Nanostructures," Physics Colloquium, University of Texas, Austin, TX, May 2, 2001.
24. D. D. Awschalom, "Manipulating and Storing Quantum Information in Semiconductors," General Physics Colloquium, California Institute of Technology, Pasadena, CA, April 26, 2001.
25. D. D. Awschalom, "Multifunctional Spintronics and Quantum Information Processing in Semicondcutor Nanostructures," Almaden Institute Symposium; Grand Challenges in Nanotechnology, IBM Almaden Research Center, San Jose, CA, April 23-25, 2001.
26. D. D. Awschalom, TBA, 10th Brazilian Workshop on Semiconductor Physics (BWSP-10), Guarujá, Brazil, April 22-27, 2001.
27. D. D. Awschalom, TBA, NATO Advanced Study Institute on Complexity from Microscopic to Macroscopic Scales: Coherence and Large Deviations, Geilo, Norway, April 17-27, 2001.
28. D. D. Awschalom, TBA, Normal Hascoe Distinguished Lecture, University of Connecticut, Storrs, CT, April 16, 2001.
29. D. D. Awschalom, Physics Colloquium, University of Minnesota, Minneapolis, MN, April 11, 2001.
30. J. A. Gupta (with D. D. Awschalom), "Coherence and Manipulation of Spin States in Semiconductor Quantum Dots," March Meeting of the American Physical Society, Seattle, WA, March 12-16, 2001.
31. J. G. E. Harris (with D. D. Awschalom), "Magnetization and Dissipation Measurements of Two-dimensional Electron Gases," March Meeting of the American Physical Society, Seattle, WA, March 12-16, 2001.
32. D. D. Awschalom (declined), Experimental Nuclear Magnetic Resonance Conference, Orlando, FL, March 11-15, 2001.
33. G. Salis (and D. D. Awschalom), "Optical Manipulation of Nuclear Spins by a Two-dimensional Electron Gas," Southwest Quantum Information Network, California Institute of Technology, Pasadena, CA, March 2-4, 2001.
34. D. D. Awschalom, "Manipulating and Storing Quantum Information in Semiconductors," Physics Colloquium, University of California, San Diego, CA, February 22, 2001.
35. D. D. Awschalom, "Manipulating and Storing Quantum Information in Semiconductors," Physical Sciences Colloquium, IBM Research Division, Almaden, CA, February 16, 2001.
36. D. D. Awschalom, TBA, Conference on Electronic Correlations: from Meso- to Nano-physics, XXXVI Rencontres de Moriond, Les Arc, France, January 20-27, 2001.
37. D. D. Awschalom, "Manipulation and Storage of Quantum Information with Semiconductor Spintronics," International conference on Experimental Implementation of Quantum Computation, Sydney, Australia, January 16-19, 2001.

38. N. Samarth (and D. D. Awschalom), "Spin Engineering in Hybrid Magnetic/ Semiconductor Hetero- and Nanostructures," Eighth Joint MMM and Intermag Conference, Austin, TX, January 7-11, 2001.
39. D. D. Awschalom, "Optical Manipulation of Nuclear Spin by a Two-dimensional Electron Gas," 31st Winter Colloquium on the Physics of Quantum Electronics (PQE2001), Snowbird, UT, January 7-11, 2001.
40. B. Beschoten (and D. D. Awschalom), "Spin Coherence and Dephasing in GAN," Heraeus-Seminar on Spin Electronics, Bad Honnef, Germany, January 2001.
41. D. D. Awschalom, "Manipulation of Electron and Nuclear Spins in Semiconductors: Coherence and Storage," 5th International Symposium on Spin-Charge-Photon Coupled Systems, Tokyo, Japan, December 13-15, 2000.
42. D. D. Awschalom (declined), Center for Magnetic Recording Research, 20th Interactive Workshop on Data Storage, Lake Arrowhead, CA, December 3-6, 2000.
43. D. D. Awschalom, "Optical Manipulation of Electron and Nuclear Spins in Semiconductors," Symposium on Ultrafast Nonlinear Optical Phenomena, Fall Meeting of the Materials Research Society, Boston, MA, November 27 – December 1, 2000.
44. I. Malajovich (and D. D. Awschalom), "Coherent Spin Transfer Across a GaAs/ZnSe Heterointerface," National Meeting of the Materials Research Society, Boston, MA, November 27 – December 1, 2000.
45. D. K. Young (and D. D. Awschalom), "Electrical Spin Injection in a Ferromagnetic Semiconductor Heterostructure," National Meeting of the Materials Research Society, Boston, MA, November 27 – December 1, 2000.
46. D. D. Awschalom (declined), Condensed Matter Physics Seminar, Department of Physics, University of Illinois, Urbana, IL, November 10, 2000.
47. D. D. Awschalom, Keynote Speaker, Canadian Institute for Advanced Research (CIAR), Symposium on the Frontiers of Nanoelectronics: Measurements and Materials, Quebec, Canada, November 3-5, 2000.
48. D. D. Awschalom (declined), Advanced Light Source Users Meeting, Lawrence Berkeley, National Laboratory, Berkeley, CA, October 16-17, 2000.
49. D. D. Awschalom (declined), Workshop on Correlated and Complex Electron Materials, University of California, Berkeley, CA, October 18, 2000.
50. D. D. Awschalom, "Manipulation and Storage of Spin Coherence in Semiconductor Nanostructures," Workshop on Electronic Properties of Mesoscopic Systems, Ascona, Switzerland, October 9-13, 2000.
51. D. D. Awschalom, "New Directions for Semiconductors: Spintronics and Quantum Computation," Plenary Lecture, 47th International Symposium of the American Vacuum Society, Boston, MA, October 2-6, 2000.
52. R. Kawakami (with D. D. Awschalom), "Engineering Ferromagnetic Semiconductors for Spintronics," Eleventh International Conference on Molecular Beam Epitaxy, Beijing, China, September 20-25, 2000
53. D. D. Awschalom, "Optical Manipulation of Electron and Nuclear Spins in Semiconductors," Plenary Lecture, 25th International Conference on the Physics of Semiconductors (ICPS-25), Osaka, Japan, September 17-22, 2000.

54. D. D. Awschalom, "Manipulation and Storage of Spin Coherence in Semiconductors," Plenary Lecture, International Symposium on the Physics and Applications of Spin-Related Phenomena in Semiconductors (PASPS 2000), Sendai, Japan, September 13-15, 2000.
55. D. D. Awschalom, "Injection, Transport and Storage of Spin Coherence in Semiconductors," International Workshop on Spintronics and Quantum Computation, Asian Technology Information Program, Tokyo, Japan, September 12, 2000.
56. D. D. Awschalom (declined), Second International Interdisciplinary Conference on Polarization Effects in Lasers, Spectroscopy, and Optoelectronics (PELS-2000), Satellite Conference to CLEO/IQEC Europe 2000, Southampton, UK, September 6-9, 2000.
57. D. D. Awschalom, "Imprinting and Manipulating Spin Coherence in Semiconductors," Symposium on Quantum Computing for the Next Millenium, American Chemical Society National Meeting, Washington, D.C., August 20-24, 2000.
58. D. D. Awschalom (declined), "Quantum Computation in Semiconductors," Workshop on Solid State Implementations of Quantum Computing, IBM Watson Research Center, Yorktown Heights, NY, August 16-18, 2000.
59. D. D. Awschalom (declined), Optical Society of America / IEEE LEOS Meeting on Nonlinear Optics, Kauai, Hawaii, August 7-11, 2000.
60. D. D. Awschalom, "Storage and Manipulation of Spin Coherence in Semiconductor Quantum Dots," QD 2000: The International Conference on Semiconductor Quantum Dots, Munich, Germany, July 31 - August 3, 2000.
61. D. D. Awschalom, "Injection, Transport, and Storage of Spin Coherence in Semiconductors,", International Symposium on Spin-Electronics, Halle/Saale, Germany, July 2-6, 2000.
62. D. D. Awschalom (declined), Seventh Annual International Conference on Composites Engineering (ICCE/7), Denver, CO, July 2-8, 2000.
63. D. D. Awschalom, "Manipulating and Storing Spin Coherence in Semiconductors," Spin Effects in Mesoscopic Systems, Euroconference, Cortona, Italy, June 28 – July 2, 2000.
64. D. D. Awschalom, "Manipulation and Storage of Spin Coherence in Semiconductors," International Conference on Induced Cooperative Phenomena, Lawrence Berkeley National Laboratory, Berkeley, CA, June 24-28, 2000.
65. D. D. Awschalom, (Declined), 8th International Symposium on Nanostructures: Physics and Technology, St. Petersburg, Russia, June 19-23, 2000.
66. D. D. Awschalom, "Spin Coherence in Semiconductors," International Conference on Macroscopic Quantum Coherence and Computing, Naples, Italy, June 14-17, 2000.
67. D. D. Awschalom, "Injection and Storage of Spin Coherence in Semiconductors," International WEH Workshop on 'Interacting Electrons in Nanostructures,' Bad Honnef, Germany, June 12-16, 2000.
68. D. D. Awschalom (declined), Symposium on Sciences that Will Affect the Future, J. Oppenheimer Study Center, Center for Nonlinear Science, Los Alamos National Laboratory, June 5-9, 2000.
69. D. D. Awschalom (declined), Keynote Speaker, Symposium on Nanoelectronics: Revolution vs. Evolution, Canadian Institute for Advanced Research (CIAR), Banff, Alberta, Canada, May 20-22, 2000.

70. D. D. Awschalom, "Optical Manipulation of Electron and Nuclear Spin States in Semiconductors," Conference on Interactions and Chaos in Mesoscopic Systems, Theoretical Physics Institute, University of Minnesota, Minneapolis, MN, May 12-14, 2000.
71. D. D. Awschalom (declined), "Brazilian National Meeting on Condensed Matter Physics (ENFMC), Sao Lourenco, Minas Gerais, Brazil, May 9-12, 2000.
72. D. D. Awschalom, "Coherent Spin Memory, Transport, and Manipulation in Semiconductors," Physics Colloquium, University of Santa Cruz, CA, April 13, 2000.
73. J. M. Kikkawa (and D. D. Awschalom), "Manipulation of Spin Information in Semiconductors by All-optical Magnetic Resonance," March 2000 Meeting of the American Physical Society, Minneapolis, MN, March 20-24, 2000.
74. B. Beschoten (and D. D. Awschalom), "Magnetic Circular Dichroism Studies of Carrier Induced Ferromagnetism in $(Ga_{1-x}Mn_x)As$," March 2000 Meeting of the American Physical Society, Minneapolis, MN, March 20-24, 2000.
75. D. K. Young (and D. D. Awschalom), "Electrical Spin Injection in a Ferromagnetic Semiconductor Heterostructure," March 2000 Meeting of the American Physical Society, Minneapolis, MN, March 20-24, 2000.
76. D. D. Awschalom (declined), International Conference on Quantum Entanglement, International Cooperative Research Project, Japan Science and Technology Corporation (JST) and the Centre National de la Recherche Scientifique (CNRS), Stanford, CA, March 20-22, 2000.
77. D. D. Awschalom, "Spins in Semiconductors," Mardi Gras Symposium, University of New Orleans, New Orleans, LA, March 2-3, 2000.
78. D. D. Awschalom (declined), "Spin-dependent Transport in Semiconductors," SPIDER Inter-European Project Meeting, Pisa, Italy, February 24-26, 2000.
79. D. D. Awschalom (declined), Physics. Colloquium, University of Toronto, Toronto, Canada, February 24, 2000.
80. J. A. Gupta (and D. D. Awschalom), "Spin Coherence in Semiconductors: Storage, Nuclear Interactions, and Transport Across Interfaces," 11th International Winterschool on New Developments in Solid State Physics, Austrian Physical Society, Mauterndorf, Austria, February 21-25, 2000.
81. D. D. Awschalom, "Manipulating and Storing Spin Coherence in Semiconductor Nanostructures," Symposium on Spintronics: Electronics for the New Millenium, 2000 American Associate for the Advancement of Science Annual Meeting, Washington, DC, February 17-22, 2000.
82. D. D. Awschalom, "Injection, Transport, and Storage of Spin Coherence in Semiconductors," 3rd International Gordon Research Conference on Magnetic Nanostructures, Ventura, CA, February 13-18, 2000.
83. D. D. Awschalom (declined), "Spin Coherence in Semiconductors," 47th Annual Western Spectroscopy Association Meeting (WSA), Pacific Grove, CA, January 26-28, 2000.
84. D. D. Awschalom (declined), Physics Colloquium, University of Utah, Salt Lake City, UT, January 20, 2000.

85. D. D. Awschalom, "Dragging, Storing, and Manipulating Spin Coherence in Semiconductors," Conference on the Physics and Chemistry of Surfaces and Interfaces (PCSI), Salt Lake City, UT, January 16-20, 2000.
86. D. D. Awschalom, "Spin Transport in Quantum Structures," International Conference on Surfaces and Interfaces of Mesoscopic Devices, Maui, Hawaii, December 5-10, 1999.
87. D. D. Awschalom (declined), Workshop on Nanoscience for High Performance Computing in Embedded Systems and Sensors, University of Alabama, Huntsville, Alabama, November 30 – December 2, 1999.
88. D. D. Awschalom (declined), Public Lecture on the Future of Nanoscience, Inauguration of the Gertrude Rempfer Endowed Chair in Electron Optics, Portland State University, Portland, OR, November 18, 1999.
89. D. D. Awschalom, "Storing, and Manipulating Spin Coherence in Semiconductor Nanostructures," 44th Annual Conference on Magnetism and Magnetic Materials, San Jose, CA, November 15-18, 1999.
90. D. D. Awschalom (declined), "Near-field Optical Microscopy of Magnetic Quantum Dots," National Meeting on Scanning Probe Microscopy, Eindhoven University of Technology, Eindhoven, The Netherlands, November 1, 1999.
91. D. D. Awschalom (declined), International Symposium on Cluster and Nanostructure Interfaces, Richmond, VA, October 25-28, 1999.
92. D. D. Awschalom, "Spin Memory and Coherence in Semiconductors," Physics Colloquium, Arizona State University, Tempe, AZ, October, 21, 1999.
93. D. D. Awschalom (declined), "Physics of Spin Technologies in Quantum Electronics," NASA-Ames Workshop on Device Modeling, Mountain View, CA, August 26-27, 1999.
94. D. D. Awschalom, "Spin Coherence in Semiconductors: Memory and Computation," National Meeting of the American Chemical Society, New Orleans, LA, August 22-26, 1999.
95. D. D. Awschalom, "Spin Coherence and Memory in Semiconductors," Conference on Quantum Magnetism in Novel Materials and Geometries, Institute for Theoretical Physics, University of California, Santa Barbara, CA, August 16-20, 1999.
96. D. D. Awschalom, "Injecting and Dragging Spin Coherence in Semiconductors," Frontiers of Magnetism – FIM99 Conference, Royal Institute of Technology, Stockholm, Sweden, August 12-15, 1999.
97. D. D. Awschalom, "Spin Coherence and Memory in Semiconductors," Southwest Quantum Information Network Meeting, Santa Barbara, CA, August 4-6, 1999.
98. D. D. Awschalom, "Spin Coherent Quantum States in Semiconductors and Quantum Dots," JASON Summer Workshop on Spintronics, San Diego, CA, July 13, 1999.
99. D. D. Awschalom (declined), "Injection and Propagation of Coherence in Quantum Systems," NATO Advanced Research Workshop on Optical Properties of Semiconductor Nanostructures, Ustron-Jaszowiec, Poland, June 13-18, 1999.
100. D. D. Awschalom, "Spin Memory and Coherence in Doped Semiconductor Heterostructures," Quantum Electronics and Laser Science Conference, Baltimore, MD, May 23-28, 1999.
101. D. D. Awschalom (declined), "Potential of Spin Electronics Using Semiconductors," International Magnetics Conference (Intermag99), Kyongju, Korea, May 18-21, 1999.

102. D. D. Awschalom, "Spin Coherence and Memory in Doped Semiconductor Heterostructures," Physical Chemistry Seminar, Department of Chemistry, University of California, Los Angeles, CA, May 10, 1999.
103. D. D. Awschalom, "Spin Coherence and Quantum Computing in Semiconductors," Southwest Quantum Information and Technology (SQuInT) Meeting, University of New Mexico, Albuquerque, NM, April 30 – May 2, 1999.
104. D. D. Awschalom, "Spin Dynamics in Semimagnetic Semiconductor Heterostructures," International Workshop on Advances in Growth and Characterization of II-VI Semiconductors, Würzburg, Germany, April 14-16, 1999.
105. J. M. Kikkawa and D. D. Awschalom, "Macroscopic Spin Transport in GaAs," Spring Meeting of the Materials Research Society, San Francisco, CA, April 5-9, 1999.
106. D. K. Young, P. A. Crowell, M. P. Mack, S. Keller, E. L. Hu, and D. D. Awschalom, "Near Field Spectroscopy of InGaN Heterostructures," Spring Meeting of the Materials Research Society, San Francisco, CA, April 5-9, 1999.
107. D. D. Awschalom, "Spin Memory and Coherence in Semiconductor Nanostructures," 4th International Symposium on Advanced Physical Fields (APF-4), Tsukuba, Japan, March 9-12, 1999.
108. D. D. Awschalom, "Spin Memory and Coherence in Semiconductors," Physics Colloquium, University of California, Berkeley, CA, February 8-9, 1999.
109. D. D. Awschalom, "Spin Coherence and Memory in Semiconductor Nanostructures," Physics Colloquium, University of California, San Diego, La Jolla, CA, February 3-4, 1999.
110. D. D. Awschalom, "Quantum Magnetism," Plenary Lecturer of the "Croucher Advanced Study Institute on the Physics and Chemistry of Nanostructured Materials," Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong, January 11-15, 1999.
111. (Declined) D. D. Awschalom, "Spin Coherence in Magnetic Quantum Structures," Dreikonigstreffen on Nanomagnetic Structures," Bad Honnef, Germany, January 4-6, 1999.